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13. ABSTRACT (Maximum 200 words)

Dredging and disposal of dredged material in aquatic environments can expose animals and plants to episodic pulses of suspended sediment. The resuspended material may then be deposited in thin layers adjacent to the dredging or disposal areas in some cases as much as several thousand meters distant. The intensity and duration of resuspension from dredging and disposal operations is highly dependent on the type of equipment, operator, character of sediment, and hydrodynamic conditions. While our understanding of the potential effects is limited, it is likely that some estuarine organisms are highly sensitive to suspended sediments and certain life stages (eggs, juveniles) may be particularly affected by resuspension and deposition.

In order to assign research priorities at the Waterways Experiment Station (WES) for designing studies on the effects of dredging-induced sedimentation, we conducted a survey of experts in sedimentation measurement and biological impacts to define existing knowledge of scales of concern for biological response to sediment deposition, methods of assessing impact, requirements for modeling, and methods of measuring deposition in laboratory and field experiments. This report summarizes the combined opinion of the panel of experts and makes recommendations for research priorities for WES investigators for the next fiscal year.

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Final Report

MEASURING RATES & EFFECTS OF DREDGING-INDUCED SEDIMENTATION: RESULTS FROM A SURVEY OF EXPERTS

Prepared for

U.S. Army Corps of Engineers
Waterways Experiment Station
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1.0 MEASURING RATES AND EFFECTS OF DREDGING-INDUCED SEDIMENTATION

Dredging and disposal of dredged material in aquatic environments can expose animals and plants to episodic pulses of suspended sediment. The resuspended material may then be deposited in thin layers adjacent to the dredging or disposal areas in some cases as much as several thousand meters distant (LaSalle et al., 1991). While the effects of elevated concentrations of total suspended solids (TSS) and thin layers of sediment on estuarine organisms are poorly understood (Wilber and Clarke, 2001; Wilber et al., in review), we do know that some of the defining characteristics of an estuarine environment are highly variable conditions in the water column for temperature, salinity and particulate flux. Thus, ambient conditions for estuarine organisms are rarely static, and most organisms are adapted to varying concentrations in suspended sediment (see bibliography in Kerr 1995). The intensity and duration of resuspension from dredging and disposal operations is highly dependent on the type of equipment, operator, character of sediment, and hydrodynamic conditions (Collins, 1995; Clarke and Wilber 2000). While our understanding of the potential effects is limited, it is likely that some estuarine organisms are highly sensitive to suspended sediments and certain life stages (eggs, juveniles) may be particularly affected by resuspension and deposition. Biological resources of concern that have been identified with this issue include:

- Submerged Aquatic Vegetation (SAV)
- Walleye (Great Lakes)
- Commercial oyster/shellfish beds
- Spawning areas for salmonids, winter flounder, & herring

The direct measurement of TSS is straightforward and can be complemented with indirect optical and acoustic measurements (optical backscatter sensors, transmissivity, acoustic doppler profiling) to achieve rapid characterization of large volumes of water over relevant spatial scales (Lohrman and Huhta, 1994; Tubman et al., 1994; Land and Bray, 1998; Puckett, 1998; Tubman and Corson 2000; Reine et al., 2002). Our understanding of the effects of TSS on salmonids and a limited number of non-salmonid estuarine fish and shellfish is sufficient to provide quantitative guidance on acceptable levels of TSS under well-studied circumstances for a few animals. Although further research is required on dose-response curves of estuarine fish and early life stages, the technology to conduct these studies is well established (Wilber and Clarke, 2001; Berry et al., 2003); dredging-induced TSS and their associated effects have been studied since the Army Corps' DMRP initiative in the 1970's. There are also well-established protocols for bioeffects testing for TSS impacts (US EPA, USACE, 1991; Caux et al., 1997); unfortunately, no such protocols exist for assessing sedimentation effects.

The measurement and assessment of effects of thick layers of sediment deposition (>1 cm) is advanced and well within the capabilities of existing technologies (e.g. Sediment Profile Imagery). It is far more difficult to reliably measure thin layers of sediment deposition from episodic events, however some techniques have been developed (Thomas and Ridd, 2004). Because ambient sediment deposition and resuspension may be of the same order of magnitude as the effects of dredging or disposal, it is particularly

difficult to isolate and quantify anthropogenic contributions to sedimentation. However, persistent concerns regarding the impacts of deposition of sediments from dredging or disposal activities on habitats, sessile shellfish and early life stages of fish require an evaluation of existing or emerging technologies for quantification of sediment deposition. Sediment deposition is also referred to as bedded sediment and is the primary focus of this assessment, as distinct from effects of suspended sediments.

1.1 Goals

In order to assign **research priorities** at the Waterways Experiment Station (WES) for designing studies on the effects of dredging-induced sedimentation, it is essential to define the critical range of parameters of concern (spatial, volume, temporal scales). Our goal was to conduct a survey of experts in sedimentation measurement and biological impacts to define existing knowledge of:

I. Scales of concern for biological response to sediment deposition
II. Methods of assessing impact
III. Requirements for modeling.
IV. Methods of measuring deposition in laboratory and field experiments.

The following scientists participated in the survey:

Name	Affiliation	Area of Expertise	Email Address
Dr. W. J. Kenworthy	NOAA/NOS Beaufort Laboratory	Submerged Aquatic Vegetation	Jud.Kenworthy@noaa.gov
Dr. K. Able	Rutgers University	Fisheries	able@imcs.rutgers.edu
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Dr. W.F. Bohlen	University of Connecticut	Boundary Layer Dynamics, Sediment Transport	bohlen@uconnvm.uconn.edu

We have compiled the responses to the survey and written a brief synthesis of our sense of the response to each question for review. In our synthesis of responses, we have attempted (very subjectively) to determine the relative completeness of the answer: <u>definitive</u> (provides clear direction to WES), <u>partial</u> (provides some direction to WES but needs more information), <u>not conclusive</u> (insufficient to provide any direction to WES). We note that none of the answers appeared to us to be "not conclusive", but most will require additional information. We also note that some of the responses have not been incorporated into our synthesis; in most cases this is due to our narrow focus on sedimentation (bedded sediments) rather than suspended load *per se*. We recognize that sediments are not likely to become bedded without having first contributed something to

the suspended load, but our intent to is to evaluate the effects of sediment <u>after</u> it has settled to the seafloor, because this has received far less research attention than suspended load. We recognize that a primary goal for regulatory action is to determine acceptable levels of effects of sedimentation on specific resources, and it is clear from this response that additional research is still required to define acceptable levels of effects (see review in Berry et al., 2003).

2.0 KEY QUESTIONS

2.1 Predicting impact (8 questions)

A. *What is the range of ambient sedimentation rates (instantaneous and cumulative) in habitats of concern?* **(Partial answer)**

The range of ambient sedimentation rates in habitats of concern are not well known and appear highly dependent on events and specific environmental conditions. However, to provide boundary conditions for field and laboratory measurements to detect change resulting from anthropogenic effects it is necessary to determine at least a range of ambient rates. Sedimentation rate is usually defined as the linear accumulation of sediment in centimeters per year (cm yr^{-1}) and may be converted into volumetric estimates of sediment flux, or mass accumulation rate (MAR), usually given in grams per square centimeter per year (g $cm^{-2}yr^{-1}$). However, effects ranges are usually expressed in responses to total suspended solids or particulate concentrations (mg L^{-1}). It is clear that for some taxa of concern, the thickness of sediment accumulation may be critical and accumulation is not the same as water column concentration (see below). It is also important to understand the range and timing of natural sedimentation events in each region or habitat. An additional confounding factor for spawning grounds is that most monitoring programs and water quality regulations for streams are expressed in turbidity (often with a narrative description, e.g., cloudy, free from color or turbidity, reduced light transmission) which may be used as a surrogate for suspended sediment concentration or siltation (Gray and Glysson, 2003).

Here is a proposed table of range of ambient sedimentation rates derived from a range of published sources:

Habitat	Sedimentation rate	Concentration near bottom
Spawning grounds (for attached eggs, gravel, sand)	Unavailable	0.1-100 mg L^{-1}
Estuarine SAV	0.1-0.3 cm yr^{-1}	10-100 mg L^{-1}
Turbid Estuaries – Fluid muds	0.3- 1.0 cm yr^{-1}	100 – 20000 mg L^{-1}

B. *What are the minimum levels of sedimentation known to have an adverse impact on early life stages of fish?* **(Partial answer)**

Available data on sedimentation expressed by concentration in the water column (potential sedimentation) does not appear to be sufficient to provide prediction of impacts

on early life stages of fish. There is a need to determine relevant scales of sediment thickness and bulk characteristics prior to larval or egg settlement and deposition of sediment after attachment or settlement. The effects of increased sedimentation resulting in "embeddedness" (fine sediment filling in gaps between gravel in streams) on hatching of salmonid eggs has been described (Waters 1995) and has resulted in guidelines based on percent fines and other variables (Lotspeich and Everest 1981 and Caux et al., 1997). Great Lakes Walleye eggs and larvae also appear to be affected by sedimentation, but laboratory dose-response data is unavailable (D. Clarke 2004 http://www.glc.org/dredging/scoop/DougClarke.pdf). A small number of direct observations and studies indicate that attachment of non-salmonid fish eggs to benthic substrata can be inhibited by siltation. Pacific herring eggs appear to require virtual absence of fine sediment layers to allow attachment to the substratum (Stacey and Hourston 1982, Haegele and Schweigert 1985, Barnhart 1988). Winter flounder eggs were observed to be affected by thin layers of deposited sediments in laboratory conditions (D. Nelson, NMFS personal communication).

Additional related information is available on the effects of both sediment transport and suspended sediment concentrations on the early life stages of fish. Lisle and Lewis (1992) provide a useful model of salmonid embryo survival based on streamflow and sediment transport. They were able to incorporate long-term streamflow records (6 years), bedload transport, a relationship between transport and infiltration of bedload and fine sediment into gravel and the result of embryo survival and gravel properties. The results of their modeling effort indicated that further research was needed to clarify how sediment transport affects the intergravel environment and in turn the potential for embryo survival. Their approach is not directly transferable to estuarine environments but might provide some framework for assessment of impacts of sediment transport in spawning areas.

Relatively high suspended sediment concentrations (> 500 mg L^{-1}) are known to have impacts on early life stages of estuarine fish (Wilber and Clark 2001, Berry et al., 2003). However, the duration of exposure to suspended sediment from dredging or disposal must be related to the type and residence time of eggs or larvae in an affected habitat. Morgan and Levings (1989) demonstrated that after settlement, development of Pacific herring larvae is delayed at very high levels of suspended sediment (10,000 mg L^{-1}). But Boehlert and Morgan (1985) reported that feeding rates of larval Pacific herring increased with increasing turbidity up to a point when feeding was inhibited (2000 mg L^{-1}). Longer-term effects of sediment deposition are highly dependent on timing of egg attachment and larval settlement which may be quite specific for a given habitat.

C. *What are the minimum levels of sedimentation known to impact early life stages of shellfish?* **(Definitive answer)**

Similar to fish, the early life stages of shellfish can be affected by passage through high concentrations of suspended sediment in the water column, but eventually shellfish must either attach to a hard substratum or burrow into appropriate sediments. Bivalve larvae appear to tolerate relatively high suspended sediment concentrations (up to 400-800 mg L^{-1} for oyster larvae and up to 2200 mg L^{-1} for quahog larvae for less than two days, Wilber and Clark 2001). Oyster larvae require a clean, hard substratum to attach, but can

tolerate thin layers of deposited sediments, perhaps up to 1 mm (Roger Mann pers. communication). After attachment, oyster larvae can tolerate deposition of 2-3 mm, with 3-5 mm and above likely to have some negative effects (Roger Mann pers. communication). Clam larvae are not likely to be affected by sediment deposited before settlement (except for potential effects on "selection" of settlement sites by larvae), but at the earliest stages, the newly settled larvae may not tolerate rapid deposition of fine sediments. Deposition rate and thickness would have to exceed the burrowing rate of the larval clams to have a negative impact. Suspended sediment and resuspended sediment (for attached or burrowing post-larvae) can affect the feeding and growth of bivalves (both larval and adult), and frequent or sustained exposure to high suspended sediment loads is clearly detrimental to most species. Field or laboratory measurements should account for stressors associated with high suspended load (including associated contaminants, ammonia and sulfides).

D. *What are the minimum levels of sedimentation known to have an adverse impact on submerged aquatic vegetation (SAV)?* **(Partial answer)**

Most assessments of loss of aquatic macrophytes have focused on impacts of changes in underwater light from increased suspended sediment (e.g., Best et al., 2001, Dennison et al., 1993). Accumulation of sediment may result in different responses among species of SAV and, in turn, different effects on sediment entrainment around SAV (Fonseca and Fisher, 1986). Assessments along gradients of siltation in SE Asia have shown loss of species and changes in species composition, supporting the potential for differential responses among species (Terrados et al., 1998). Effects of deposition may also be difficult to separate from associated effects of increased sediment flux including light attenuation (Terrados et al., 1998). Unfortunately, field assessments of effects of siltation or deposition on SAV in U.S. waters is very limited.

Successful settlement of kelp and other algal species on hard bottom substrata is clearly inhibited by very thin layers of sediment (0.008 mm). *Fucus serratus* embryos responded negatively to thicker layers of sediment, with a stronger negative reaction to fine and organically enriched sediments, and most strongly to the presence of sulfide (Chapman and Fletcher, 2002).

Because SAV may have a very wide range of growth forms, sizes and phenotypic plasticity, the effects of deposition could vary considerably depending on habitat, season and water depth. Deposition may affect growth and survival due to light limitation, accumulation of waste products due to limited diffusion and sulfide poisoning depending on grain size, water content, and organic content of sediments.

E. *How are relevant levels of sedimentation best expressed (thickness, volume, dry/wt weight)?* **(Definitive answer)**

Measurements of sedimentation (i.e., bedded sediments) relevant to biological effects may require several dimensional variables including thickness, density, percent fines, geometric mean size, and Fredle number (Caux et al., 1997). Fredle number is an index of permeability that has been correlated with survival to emergence of salmon and trout

(Lotspeich and Everest, 1981). Hinchey et al., (in review) chose effective overburden stress (kPa: bulk density and depth of burial, Richards et al., 1974) as a reliable measure of the force exerted on organisms by sediment burial because it combines burial thickness and porosity. Their experiments with sediments from the Chesapeake Bay and York River were conducted to assess survival at 6 days of burial for a range of overburden thickness (0-25 cm) representing overburden stress from 0-16 kPa (Figure 1). Force may be most important to mobile organisms attempting to escape from deposition events, but permeability may be more important to the survival and growth of sessile organisms buried under very thin layers of sediment (< 2mm).

It appears that the consensus is that a combination of mass and some form of bulk density may be the most widely useful characterizations, but that grain size and permeability may have important applications. Even the apparently simplest variable, thickness, may be quite difficult to measure *in situ* (see below) at the lower end of the ambient range (0.1-0.3 cm).

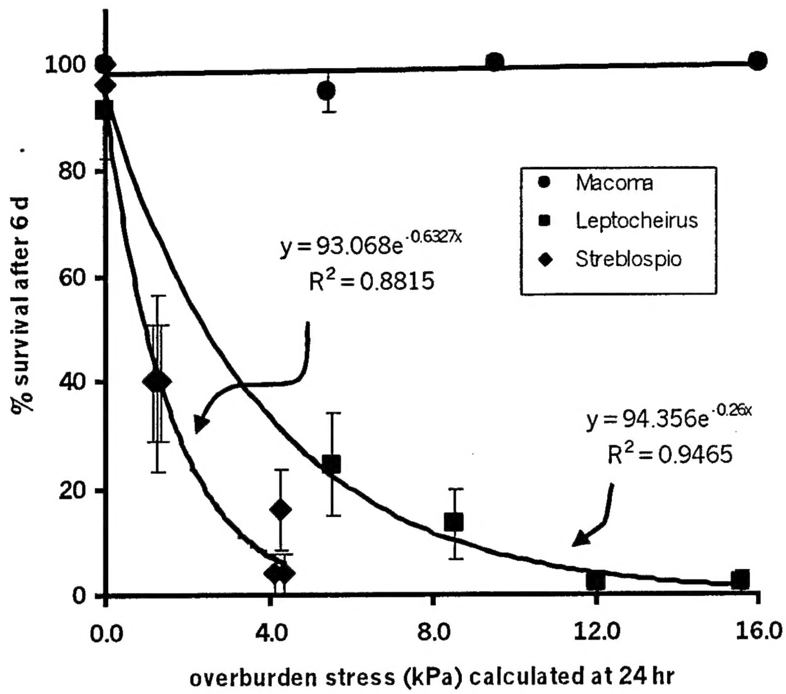

Figure 1. Percent survival of three benthic invertebrates to vary overburden stress after 6 days of burial. From Hinchey et. al., (in review).

F. *What are the temporal scales of concern for impacts from sedimentation?* **(Definitive answer)**

Temporal scales of concern can be seen at several levels: duration of external event (days), timing of external events (seasons), persistence of the effects of external events (weeks). Taking each in turn, we can provide some boundaries for field and laboratory investigations. Duration of external event: assuming that sedimentation results from dredging or disposal events, dredging operations would likely move past an area of

potential impact in 1-5 days, disposal operations would potentially last longer with episodic plumes or density currents depositing fresh layers of sediment. The former would approximate the duration of storm-induced disturbance, whereas the latter might approach chronic, recurring frequency during one or more seasons. Timing of external events: the scale of concern for timing of external events is closely related to the key seasonal events of reproduction and critical life stages or presence of organisms in the vicinity of the event(s). Persistence of effects of external events: in most sediment systems, newly settled sediment is subjected to biological and physical mixing to a degree immediately after placement. How quickly bedded sediments are incorporated into ambient sediments or re-transported is highly dependent on hydrodynamics and the ambient biological community. In some habitats, the introduction of fine sediments (for example, into coarse sands or gravel) might induce settlement and colonization of new populations altering the community and potentially further affecting species of concern or mediating the effects of the sedimentations. Regardless, the time constant for assimilation of bedded sediments into some level of equilibrium is likely to be on the order of weeks. If silts become "embedded" into coarse sands or gravels, they may become resistant to erosion (it is harder to resuspend a fine cohesive particle [consolidated] than a larger grain size non-cohesive particle).

G. *What is the minimum length scale for time of sediment accumulation?* **(Definitive answer)**

The intent of this question was to understand what might be the shortest (most ephemeral) sedimentation event of concern. Based on responses above, events of hours or days could create impacts, but assessment of impacts should be longer than one day (suggested time is 3-5 days).

H. *What are the most sensitive biological resources to evaluate? Please rank in order of priority.* **(Definitive answer)**

It is important to note that eggs and larvae of marine species typically suffer very high mortalities. While preventable sources of mortality are not welcome or meaningless, they must be of sufficient scale to have a measurable effect on population size or locally significant recruitment to overcome costs or effects of prevention. Assessment of effects on population size will likely require modeling rather than observation. We have refined the list to focus on direct effects of bedded sediments to provide direction for focused research, recognizing that water column effects are also significant but outside the scope of this project.

1. Eggs of benthic fishes failing to attach, grow or hatch. This may be the most sensitive resource, and it would be a very high priority if sedimentation at a site had the potential to cause the loss of an entire year class.
2. Non-burrowing substrate organisms, SAV, shell reefs (oysters). This may not be most sensitive (with the exception of some kelp), but loss or impairment (growth, reproduction) would require long recovery time (long-lived, difficult to establish stable population).
3. Eggs and larvae of pelagic fish if near bottom. Many pelagic fish have eggs or early life stages that settle to the bottom and may be affected by bedded sediment.

4. Avoidance or failure of spawning by adults due to sudden presence of sediments. This response has the potential to be the most devastating to a population, but unless the species has a very high site affinity or disturbance is very widespread, it will be difficult to assess whether adults successfully spawn elsewhere. May be amenable to modeling.
5. Metamorphosis of benthic life stages of fish. Little is known of the effects of sediment on this process, but it has the potential to affect a critical life stage.
6. Juvenile fish. Both pelagic and benthic fish are likely to be vulnerable to predation and/or restriction of food supply if they avoid areas due to sedimentation.
7. Sessile benthic invertebrates. The most sensitive would include non-burrowing filter feeders (apart from shell reefs above) followed by interface feeders.
8. Benthic fish. Benthic fish can have high affinity to specific substrate types but are also capable of relocating during the assimilation of the bedded sediments. Relocation may subject fish to increased predation or loss of foraging area.
9. Burrowing benthic invertebrates. Relatively high overburden stress would be required to affect burrowing invertebrates, but this may scale with the size of the organism.
10. Pelagic fish. Pelagic fish are least likely to be sensitive to bedded sediments, but may react to effects on food resources.

2.2 Evaluating impact (4 questions)

A. *What are appropriate laboratory time scales for measuring impact of sedimentation on fish/shellfish/SAV?* **(Definitive answer)**

Laboratory time scales should reflect assumptions of field effects; duration of event, 3-5 days; assessment of impacts:

- Adhesion of herring eggs in presence of varying concentrations of sediments
- Fertilization success of eggs in presence of sediments
- Developmental success and hatching (days to weeks)
- Larval behavior and feeding: minutes to hours
- Development of kelp: hours to days
- Long-term effects on adults: SAV growth and physiology-hours to weeks

B. *What are appropriate laboratory volume scales for measuring impact of sedimentation on fish/shellfish/SAV?* **(Partial answer)**

This will depend on scale of organism and mass or volume of bedded layer. Based on species and life stages of concern, benthic fish eggs and larvae are highest priority and may be most tractable based on scale. Eggs and embryos can be on the milliliter scale (see Chapman and Fletcher 2002), whereas larvae and juveniles may require many liters to even mesocosm scales. Complexity of scaling effects becomes more difficult as the scale of organism increases.

C. *What are appropriate* <u>*in-situ*</u> *time scales for measuring impact of sedimentation on fish/shellfish/SAV?* **(Partial answer)**

Short-term measurements are most likely to capture direct effects of sedimentation events, could extend from hours to 3-5 days. Longer-term measurements are likely to be confounded by natural resuspension and settlement events but might detect more subtle impacts if paired with adequate controls. Longer term might require an entire recruitment to grow out with a cycle of months to years.

D. *What are appropriate in situ volume scales for measuring impact of sedimentation on fish/shellfish/SAV?* **(Definitive answer)**

Evaluate the initial mixing zone and extent of any density flows adjacent to the dredging or disposal event(s). Spatial extent of measurable sedimentation could range from 200 – 1,000 m away from source but strongest effects will occur up to 300 m from source.

2.3 Modeling (2 questions)

A. *What resuspension or sedimentation input data are needed for validation of models?* **(Partial answer)**

The <u>characteristics</u> of resuspension are explicitly provided to all currently operational models (both the loss rates as well as the production rates are input variables), but there are no models of resuspension per se unless one considers empirical algorithms as models. However, additional field data providing a direct measure of suspended material concentrations at various points over the vertical and at various distances downstream of the operating dredge are always of value. The increasing use of acoustic techniques should improve our 2-d understanding of plume structure; if the detail over the vertical is added, we might be able to finally come to some agreement on the character of the plume resulting from both hydraulic and clam shell dredging operations. The achievement of this goal requires close collaboration between scientists/engineers and dredge operators as well as a bit of luck.

The variety of models detailing sedimentation of materials placed in suspension by dredging would benefit from direct measures of the resulting deposit characteristics (3-d measurements) following completion of dredging. This might be best realized by high resolution measurements of short-lived radionuclides, e.g. ^{7}Be, from diver-placed cores obtained before and after dredging at selected points along and across mapped plume trajectory. In some cases, these measurements would be complemented nicely by sediment profile camera data. These latter observations might only work if placement of the camera was very accurately controlled (staked locations, diver assisted) and the thickness of deposition was in excess of ~ 0.5 cm. The latter criteria suggest that measurements would be best used in the initial mixing zone – the area characterized by an exponential decrease in suspended material concentration with distance.

B. *What are the limiting factors in existing models?* **(Partial answer)**

All models suffer from a less than perfect way to handle settling velocities. Because gravitational settling is the primary process driving the resuspended materials to the

bottom, this parameter must be accurately defined. Most of the models struggle with this to a greater or lesser degree. Work is in progress but more needs to be done.

All of the existing models considered (TASS, SSFATE, STFATE, Newcombe-Jensen, DREDGE) are fundamentally advection/diffusion formulations dealing with the dispersion of sediments emanating from a source. The sediments are carried by the local flows and settle to the bed. Once on the bottom they stay in place. There is no consideration of subsequent resuspension and transport and/or mixing with ambient sediments. This is a major deficiency. Freshly deposited sediments are subject to nearly immediate resuspension and mixing with the ambient suspended material field. Such mixing has the potential to significantly reduce the effect of the newly introduced sediments on the benthic community. It also may serve to complicate the establishment of cause and effect relationships. A model that provides a means to quantify the extent and timing of mixing along the sediment-water interface should be considered an element essential to any effort to quantitatively define the biological impacts of dredge-induced sedimentation.

Another type of available model is the dynamic energy budget (DEB) individual-based model (Noonburg et al., 1998; Nisbet et al., 2000) to predict effects of stress on organism growth and survival. These models need detailed lab data for input (growth, respiration, survival) in response to sediment exposure. They are very useful for specific predictions on impacts and how to link these individual effects to population responses. However, these require detailed laboratory results on response of specific organisms to bedded sediments and should be considered as potential candidates for second-order research priorities.

2.4 Comments?

Is there any issue/item/topic that we have not asked that you think would be important or relevant information to consider as part of this task? Please feel free to include any thoughts that cross your mind.

<u>Impacts from dredging other than sedimentation</u>: While the focus on TSS is appropriate in many studies of dredging-induced sedimentation, it is not clear why this is the only variable of concern. What about the role of contaminants, dissolved oxygen, etc. as associated with resuspension of sediments?

<u>Frequency, duration, and magnitude of TSS:</u> Assuming for the moment that the response to TSS is appropriate, it is very important to evaluate TSS relative to the frequency, duration and magnitude of ambient perturbations that cause TSS. Some additional perspective on this can be found in the papers by DeAlteris et al. (1999) and Sullivan et al. (2003).

<u>Regional differences in biological responses:</u> Just as there are important variables such as species and life history stage variation that influences fish response to TSS, there are also particular responses that differ from region to region. For example, in the Mid Atlantic Bight (Cape Cod to Cape Hatteras) there is considerable more seasonal variation in the fish fauna then there is to the north (Gulf of Maine) and to the south (South

Atlantic Bight). As a result, the fishes in the Mid Atlantic Bight are highly seasonal and migratory, thus the response to dredging activity is highly seasonal and this should receive much more attention than it currently does. The same kinds of regional variation may apply in other parts of the U.S.

Additional issues for impacts to fish resources: Because Pacific herring is a prime concern with this issue, it is critical to understand its reproductive biology when considering potential impacts. These issues are also relevant to other organisms. They include:

1. Interference of egg adhesion by sediments. Coating fertilized eggs with sediment is actually a very useful technique in hatcheries (sturgeon and others) where adhesion of eggs to each other results in low oxygenation and fungal growth. Sediments coat the egg chorion and prevent adhesion. However, this will result in embryo loss from the habitat and it has been established that for herring, any non-adhering embryos will not survive to hatching.
2. Interference of fertilization by sediments. Fish eggs have a single micropyle (channel in chorion) where sperm enter and fertilize. If chorion is covered with sediment, it is likely that fertilization rates will be low.
3. Contaminants associated with suspension of sediments. This is well established for metals and some organics. Sediments act as a sink for the worst of the contaminants in freshwater, estuarine and marine sediments. In suburban estuaries, resuspension of sediments will introduce a massive dose of pollutants into the water column. While this is relatively short-lived depending on outflow and tidal flushing, many contaminants remain associated with the sediments. Contact of these sediments with the fish embryos can result in dramatic toxic effects (Hollert et al., 2003). Long-shore effects need to be considered (i.e. we need to know where sediments and water column contaminants go after they dissipate from specific site).
4. Harbor sediments are known to have high levels of ammonia and sulfide. These are extremely toxic to embryos as well as adult organisms (Stronkhorst et al., 2003). While these are not persistent, they can have dramatic effects on biota locally.
5. Dredging and sedimentation during non-spawning periods needs to be carefully evaluated. Herring exhibit homing behavior and it is not known what specific factors attract the reproductive adults to specific regions of an estuary. It has been suggested that these spawning adults may even represent separate stocks (genetically distinct?) of the main estuary population since they exhibit differential sensitivity to environmental factors such as salinity.

   The effects of sediments on habitat (SAV, coating hard bottoms, etc.) or on larval food supplies (crustacean and mollusc populations) months prior to spawning activities may impact fish selection of spawning areas.

Overall, limiting consideration of potential impacts due to sediments per se is short-sighted. All of the factors associated with sediment suspension in estuaries must be considered, with only one of these being the physical effects of particulates.

Impacts at organizational levels higher than individual species: It's important to expand the focus beyond potential impacts on individual species. While these are of course important, there is always the potential, especially in estuarine systems, for indirect, cumulative, and/or cascading effects that have repercussions for whole communities. These larger impacts are admittedly much more difficult to conceive of, predict in any meaningful way, and/or model. Any monitoring program should develop a couple of simple scenarios for higher-level impacts and have the ability to monitor for those.

Up-front statistical design and power analyses: It's important in any monitoring program to use statistical design tools up front. The most important of these are conceptual modeling (at the front end of the design process) and statistical power analysis (at the tail end of the design process). Without good conceptual models, the monitoring program runs a substantial risk of monitoring the wrong things. Without thorough power analyses, any monitoring program runs a very large risk of either oversampling (and wasting money) or undersampling (and wasting money by not obtaining useful information).

If trends over time are an issue, which they are in many ambient monitoring programs, then power analyses can also provide some realistic bounds on when an answer might be available. In many environments, trends are not visible for many years, even when they exist. Estimates from power analysis about how long this waiting period might be can be extremely useful in managing expectations of managers and advocacy groups. For example, the use of power analysis in the design of stormwater monitoring programs in southern California has been useful in lengthening the time horizons for management.

Habituation of biological responses: The issue of acclimatization should not be overlooked. Is it possible for organisms to adapt. This would seemingly make it difficult to conduct meaningful laboratory experiments. None of the above questions seems to take such effects into account.

Knowing background conditions: The establishment of background conditions prior to the initiation of any studies of the impacts of dredging-induced sedimentation. We have an abundance of data (reasonably long term) detailing background conditions at a variety of locations. Some of these sites are said to be productive shellfish beds. Time series data show high suspended material concentrations for extended periods of time. These data would suggest that both oysters and clams can tolerate reasonably high concentrations of suspended material concentrations for some period of the year. Possibly it's a case of concentrations being relatively low in the summer months, allowing spawning, settlement, and adaptation sufficient to tolerate high concentrations during the colder months of the years when metabolism slows ?

Creating accurate boundary layer conditions in the laboratory: The character of the sediment-water interface seems to be generally neglected or misunderstood. The sediment-water interfacial region is typically characterized by a high degree of spatial and temporal variability. There's continuous re-cycling of sediments to and through this region. Because filter-feeding organisms live in this region, it suggests that they can tolerate ambient concentrations and the associated temporal variability. If a laboratory experiment intended to simulate these conditions, it would have to expose test organisms

(both plant and/or animal) to a time-variant suspended material concentration and associated transport system. There are very few labs able to produce such conditions. The above questions don't seem to accommodate this need unless we include it in discussions of laboratory time scales.

3.0 CONCLUSIONS

The US Army Corps of Engineers Waterways Experiment Station has been studying the environmental effects of dredging for over 3 decades, and the impacts from sediment resuspension during both dredging and disposal have long been a focus of study as well as a major source of concern among resource agencies. The potential detrimental effects of sediment resuspension fall into two categories: exposure to and impacts from suspended sediment in the water column, and sedimentation effects. While the former has been an active area of investigation, the latter has not received as much attention. One key reason for this has been the difficulty of measuring sedimentation on short time scales and at small quantities as well as measuring the effects of dredging-induced sedimentation on biological resources.

Given the earlier recommendations from our panel of experts on the necessary measurement scales for prediction of impacts and inputs for modeling, a brief review of the available monitoring techniques available as well as recommendations for future studies to measure sedimentation on fine scales is in order. There are two potential arenas of monitoring for sedimentation effects: the direct measurement of small-scale sedimentation events from dredging, and the biological responses to those particular events.

3.1 Direct Measurements of Sedimentation

Obviously, the first-order question about sedimentation impacts from dredging-related operations would be how much is accumulating over how large an area and at what rate. Before any efforts could be launched at studying biological responses, it is necessary to know the scale at which the potential problem or "impact zone" exists. McKee et al. (1983) define sediment accumulation as "the net sum of many episodes of sediment deposition and removal", i.e., a primary flux of particles that would settle for the first time, and a secondary flux of resuspended particles that settle for a multiple number of times. While a wide variety of instrumentation (such as acoustic and optical backscatter sensors, pressure sensors and laser *in-situ* scattering and transmissometry [LISST] sensors) exists to acquire time-series measurements of suspended sediment in the water column (the source for the primary flux of particles), monitoring water column suspended sediment concentrations alone would not provide adequate information to calculate or infer total sediment accumulation at a particular location. A useful review of technologies used for turbidity and suspended sediment measurement is in Gray and Glysson (2003) including a technology information matrix. Time-series water column measurements, no matter how accurate, would not account for medium- and long-term sediment resuspension, sediment decomposition or dissolution, compaction, medium- and long-term erosion, and longer-term net accumulation (Thomas and Ridd, 2004). In order to quantify the scale of sedimentation from dredging operations, measurements of sediment accumulation would have to be made directly on the seafloor.

Two types of monitoring techniques are available to quantify sediment accumulation: discontinuous and quasi-continuous. The discontinuous methods are most common (and

the least expensive); they require an observer to go to the particular location of interest and take a reading or a sample to estimate an average rate of accumulation over the observation period. As a result, surveys using this approach are either short in duration (e.g., 24 hours) or have a long observation interval (days to weeks) and do not allow for extensive high frequency time variability analyses (Thomas and Ridd, 2004). In order to get a handle on time variability analyses, several techniques have been developed that allow quasi-continuous measurements to relate accumulation processes to small time scale processes such as tides, currents, storms, or dredging events. These instruments are more elaborate and expensive than discontinuous methods because they involve *in-situ* data loggers. However, they have the tremendous advantage of being less labor-intensive (multiple boat trips and dive operations are not necessary for observation or sample collection), and their sampling frequency is limited only by the electronic logging capabilities and/or fouling resistance of instrument sensors.

The following table summarizing available monitoring techniques is taken from Thomas and Ridd (2004; Table 1) with some modifications and additions. The time resolution of each method is dependent on the type of measurement: the time interval for discontinuous methods is the observation interval, while the interval for continuous methods is the logging interval.

Available Methods for Measuring Short-term Sediment Accumulation

Method	Reference	Vertical Resolution	Accuracy	Spatial coverage	Cost	Type*
Marker horizon	Cahoon & Turner (1989)	1 mm	33-86% reported	1-10 m	Low to medium	D
Sediment traps	Butman (1986)	NA	NA	trap diameter	Low to medium	D
OBS (sediment accumulation sensor)	Ridd et al. (2001);Thomas et al. (2002)	0.2 µm	70% or less in moving water	Point	High	C
OBS (sedimeter)	Erlingsson (1991)	0.1 mm	NA	Point	Medium	C
Centurion® Time-Series trap	Partrac, Ltd	Unknown	Unknown	Point	High	C
Digital Sedimentation Camera	Ocean Imaging Systems	0.5 mm	Unknown	10 cm	Medium to high	C

***Type:** D = discontinuous; C = Continuous

3.1.1 Discontinuous Methods

3.1.1.1 Marker Horizon Method

This method is quite simple and consists of spreading a marked layer (horizon) of unique material at the start of the study on the existing sediment surface; typical markers include feldspar, clay, brick dust, sand, glitter, fluorescent particles, or sediment laden with rare earth elements. At chosen intervals (typically on the order of months), a core is taken at

the site and the depth of the horizon below the new surface is recorded. A variant of this technique is to bury a metal plate and then measure the depth of sediment on the plate with a ruler to the nearest millimeter (not convenient for underwater studies). This can be an inexpensive method (except when rare earth elements are used) and amenable for measurements at multiple sites along a distance gradient. However, there are also numerous disadvantages, including:

- the density of the marker being different than the sediment being measured
- the large quantity of marker needed to yield an easily discernible layer
- potential disturbance of the horizon by bioturbation or periodic erosion
- smearing by coring due to wall friction
- the ability to re-locate the area by divers where the marker has been spread

3.1.1.2 Sediment Trap Method

Even though sediment traps have been used in a large number of studies to estimate vertical particle movements, there is no ideal design (Gardner, 1980a). Cylindrical traps/tubes are normally used, but there is no accepted standard for the proper trap aspect ratio (trap height to aperture diameter). Even though ratio values can vary from as low as 0.15 up to 6 (Gardner, 1980b; Ridd et al. 2001), there is still no agreement on the preferred design after more than 2 decades of debate (see Thomas and Ridd, 2004, for more details). In order to improve the temporal resolution, more elaborate trap systems called time-series or sequential traps have been designed that collect several samples in a deployment system with the help of a rotating tray, replacing the active collecting trap at a programmed interval (Bale, 1998; Lund-Hansen et al., 1997). However, despite the automated design, sampling frequency remains relatively low (once per tide or once per day).

Sediment traps provide spot measurements of sediment accumulation and offer some undeniable advantages: they are simple, hardy, cheap, and can be used in the intertidal zone to deep water. Because of these, they have become one of the most common methods for estimating sediment accumulation. However, the disadvantages of sediment traps are that they provide very biased measurements in flowing water regimes (Bale, 1998; Gardner, 1980b), and the over- or under-trapping (trap collection efficiency) depends on trap geometry, suspended sediment concentration, size and density of sediment particles, and current velocity and direction. Therefore, it's impossible to define the accuracy of trap measurements, and these difficulties worsen for very small-scale accumulations (less than 1 mm; see Thomas and Ridd, 2004). Investigators have used sediment traps to look at settlement of scallop dredge plumes, but these have been under controlled event operations and the traps collected after one pass of the dredge (Black and Parry, 1999); this approach would clearly be impractical for studying sedimentation along a gradient away from an active channel dredging operation.

3.1.2 Continuous Methods

3.1.2.1 Optical Backscatter Sensors

There are 3 different ways that optical backscatter sensors can be used to measure sediment accumulation. The first (and most conventional) is to calibrate the instrument to suspended sediment concentrations (SSC) and then recording SSC changes quasi-continuously at different locations. If water column SSC measurements were the preferred option for a particular monitoring program, then LISST sensors would be preferable to OBS sensors because of their increased accuracy (Agrawal and Pottsmith, 2004). However, as outlined above, there can be substantial errors from inferring sediment accumulation from SSC water column measurements alone. At present LISST sensors have not been configured to interrogate water volumes near the seabed, although a new device (LISST-SL) has been designed for streams to sample water within 10 cm of the bed (C. Pottsmith, pers. comm..September, 2004).

The second method involves orienting the OBS so that it faces upward and particles accumulate on the sensor (Ridd et al., 2001). The OBS response increases as particles accumulate on the sensor, and the output is correlated with the amount of accumulated sediment and recorded on a submersible data logger. A wiper cleans the sensor at chosen intervals (that hopefully have been set at the right frequency so that the signal isn't obliterated by too much sediment accumulation). The advantages of this technique are that it combines a high temporal resolution (order of minutes) with a long deployment (order of weeks or months); laboratory calibrations have shown the vertical resolution to be 0.01 mg cm^{-2} with accuracy around 70% in flowing water. However, the disadvantages include: a) relatively high cost; b) dependence on the wiping mechanism (which can be hindered by mechanical reasons or animal interference); c) limitation on the sediment thickness that causes optical saturation; and, d) a difference in surface characteristics between the sensor plate and the surrounding sediment.

The final method is the Sedimeter, an adaptation of OBS technology into a vertical array of sideways-pointing infrared sensors within a transparent rod (Erlingsson, 1991). The rod is planted in the seafloor and connected to an underwater data logger; as sediments accumulate, compact, or erode, then more or fewer sensors receive a backscattered signal, indicating the changing level of the sediment-water interface over time. A resolution of 0.1 mm was achieved in the laboratory, but accuracy was not specified (Erlingsson, 1991); these instruments are available commercially and the cost is approximately $6,000 per unit (http://www.erlingsson.com/Sedimeter/Sedimeter.html). The advantages of this approach are the same for the upward looking OBS; the one minor disadvantage to this approach is the disturbance of local flow hydrodynamics around the instrument (but this is true of all these monitoring techniques).

3.1.2.2 Centurion® Time-Series Particle Trap

Partrac, Ltd in the United Kingdom has just developed a time-series sediment trap that collects suspended material moving horizontally in a fluid and time-stamps the arrival period of particles. Because the instrument is currently under patent review, there are very few details available on the design or exact specifications. We were able to find out

from the manufacturer that the instrument measures flow direction, turbidity, pressure (depth) and temperature, with logging capabilities for additional sensors. The trap is capable of remote operation to a depth of 1000 meters for a period of up to 40 days. They cite the main advantages to this trap are the cost savings available by eliminating the need or multiple boat trips for equipment sampling/servicing/information downloading and the inclusion of time-series information. Until the design specifications are released with more details, it is difficult to know what the potential disadvantages are other than the relatively high cost per instrument (approximately $22,400) for these point measurements.

3.1.2.3 Digital Sedimentation Camera

Sediment profile imaging has been used to map thin layers of sediment accumulation on the aprons of dredged material disposal site deposits (Germano, 1983; Rhoads and Germano, 1990; Germano, 2003) after disposal operations have been completed. However, with the recent modifications made to the sediment profile camera for time-lapse imaging (Diaz and Cutter, 2001; Solan and Kennedy, 2002), it could be adapted for studying small-scale sediment accumulation from dredging operations with some further modifications. We contacted the manufacturer of the camera (Ocean Imaging Systems, North Falmouth, MA) and gave them the specifications for a shallow-water, diver-deployed camera that could be buried in the sediment and have a low/minimal profile projecting above the sediment-water interface so as to minimize the disturbance of local flow hydrodynamics. They quickly responded with a concept drawing for a 6-megapixel digital camera in a cylindrical housing that could be buried in the mud with anchor stakes and stabilizing plates and an image size of 15 cm by 10 cm; depth rating would be ~100 ft and image capacity would be 500 images with user-selected intervals for the time-lapse recording. To recover the non-recurring engineering costs, the price was amortized over an initial purchase of 10 units to be deployed at various locations around a dredging operation, with a cost of $14,100 per camera. The resolution of the camera in the horizontal direction (fewest number of pixels) would be approximately 0.01 mm.

The advantages of this system are similar to the sedimeter and upward-looking OBS (high temporal resolution, long deployment) but with the added advantage of optical images that would allow the investigator to see the pulses and type of sediment accumulating as well as the biological response of the benthos to those sediment accumulation layers. The one minor disadvantage is the local disturbance of hydrodynamic flow regimes.

3.2 Monitoring Biological Responses to Sedimentation Events

Of the biological resources of concern listed earlier (SAV, commercial shellfish beds, fish, and spawning areas), the first two are very amenable to conventional monitoring techniques to assess physiological responses of the organisms because they are stationary. For monitoring the response of fish to sedimentation events in the field, the available techniques would vary with the location and scale of the sedimentation event. Once that is known, monitoring the behavioral responses of fish would be most instructive. Current tagging technologies provide a number of possibilities for both juvenile and adult fishes in order to measure behavioral responses.

Monitoring the effects/responses to spawning areas would be much more complicated; possibilities exist for monitoring both gamete/larvae reactions as well as adult spawning behavior through the use of quantitative motion analysis (Dutta et al., 1989; Gerlich et al., 2003). While this offers the potential for addressing the effects of suspended sediment particles on swimming speeds, velocity, orientation of either adults or gametes, it is more amenable to laboratory studies rather than field monitoring efforts. While some new emerging technologies using motion analysis are being developed in the medical diagnostic field (wearable accelerometric dataloggers) for assessing movement disorders (Sableman et al., in prep) that hold potential for studying adult fish movements, it will be some time before these would be affordable or could be adapted for marine organisms in either laboratory or field studies

3.3 Recommendations

Because knowing the "scale at which the problem exists" is a first-order question, our recommendation to WES as far as research priorities for the short-term would be to invest in appropriate instrumentation and perform field trials at a number of different field sites with different types of dredging operations (e.g., clamshell, cutterhead, and trailer suction dredge) to determine:

- the area of seafloor affected by sediment accumulation from dredging operations;
- the vertical height of these accumulated layers;
- the timescale over which these accumulations develop.

Of the available technologies reviewed that would provide the information needed with the required quantitative and temporal resolution for the biological resources of concern, the two that appear most promising are the Sedimeter and the Digital Sedimentation Camera (once more information is available on the Centurion® Particle Trap, this may be worth some preliminary field trials). Both monitoring systems would require divers for deployment and retrieval, so actual operational costs for field measurements would be identical. While the Sedimeter offers a definite cost savings over the time-lapse profile imaging (about 42% of the cost on a per-unit basis), it has the disadvantage of providing "blind information"; one would not be sure if the time-series signal being measured is due to actual sediment layers accumulating/eroding or temporary fouling (trapped SAV, crabs or snails attracted to the instrument, etc.). Ideally, both systems could be acquired and deployed for a comparison of which would provide the best quality information for the research objectives.

Once some definite data are acquired so that the scale of sedimentation is known, it would then make sense to re-visit this issue to see which biological resources of concern are truly at risk from dredging operations in order to decide what the appropriate monitoring tools would be to assess biological impacts.

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